

Flexural Capacity Evaluation of OTEC Piping System: Finite Element Analysis and Governing Formula

Hensa Akbar Al Kautsar^{1,2}, Ristiyanto Adiputra², Bambang Kusharjanta¹, Aditya Rio Prabowo^{1,3}, Navik Puryantini², Gerry Giliant Salamena⁴, Bondan Fiqi Riyalda⁵, Oleksi Melnyk⁶ and Martin Jurkovič⁷

Received: 28 February 2025 / Accepted: 24 April 2025

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Abstract

The application of renewable energy plays a crucial role in advancing sustainable development, with one such source being ocean thermal energy conversion (OTEC). OTEC systems harness the temperature difference between sea surface water and deep seawater to generate electricity. A key component of the OTEC system is the piping network, which, despite its importance, has not been extensively studied. Thus, the current study aims to investigate how geometric variations and material properties affect pipe strength and to develop a predictive formula for estimating the pipe's bending capacity. The analysis uses the finite element method (FEM), starting with a validation phase against previous studies to ensure the accuracy of the scenario and test module settings. A simulation case study is then conducted, focusing on pipe bending by varying pipe geometry and material yield stress. The results of the variation analysis show that each parameter substantially impacts pipe performance. Specifically, a smaller length-to-diameter (L/D) ratio results in a stiffer pipe, as does a smaller diameter-to-thickness (D/t) ratio. In addition, materials with low yield strength deform easily. Using the test data, a nonlinear regression model was developed to generate a predictive formula for estimating the ultimate flexural capacity of the pipe. The validation results of this formula show that the developed equation is highly accurate and outperforms existing empirical formulas. This study provides valuable insights for designing efficient and optimized OTEC piping systems, offering a fast and accurate estimation tool.

Keywords Renewable energy structure; Cylindrical shell; Ultimate bending moment; Nonlinear regression; Governing equation

Article Highlights

- A comprehensive finite element analysis was conducted to assess the impact of geometric and material variations on the flexural capacity of pipes used in OTEC systems.
- Parametric simulations demonstrated that pipe length, L/D and D/t ratios, and yield strength substantially influence pipe stiffness and deformation behavior under bending loads.
- A new predictive formula for estimating the ultimate bending moment of pipes was developed using nonlinear regression based on FEM results from over 300 simulations.
- The proposed governing equation achieved an average prediction error of only 3.62%, outperforming multiple existing empirical models.
- This study provides a practical and accurate tool for quickly assessing and designing safe and efficient piping systems in OTEC applications.

✉ Ristiyanto Adiputra - Aditya Rio Prabowo
ristiyanto.adiputra@brin.go.id - aditya@ft.uns.ac.id

¹ Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

² Research Center for Hydrodynamics Technology, National Research and Innovation Agency (BRIN), Surabaya 60112, Indonesia

³ Laboratory of Design and Computational Mechanics, Faculty of Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

⁴ Research Center for Deep Sea, National Research and Innovation Agency (BRIN), Tangerang Selatan 15310, Indonesia

⁵ Directorate of Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency (BRIN), Jakarta 10340, Indonesia

⁶ Department of Navigation and Maritime Safety, Odesa National Maritime University, Odesa 65000, Ukraine

⁷ Faculty of Operation and Economics of Transport and Communication, University of Žilina, Žilina 01026, Slovakia

1 Introduction

Global efforts to create an environmentally friendly way of life have encouraged the development and adoption of renewable energy as a substitute for fossil energy sources (Alanazi et al., 2023; Fauzi et al., 2024; Fajri et al., 2024; Ladokun et al., 2024; Rosli et al., 2025; Shame et al., 2025). One potential renewable energy source is ocean thermal energy conversion (OTEC), which harnesses the temperature difference between warm surface seawater and cold deep seawater as an energy source (Masutani and Takahashi, 2001; Syamsuddin et al., 2015). Similar to other green harvesting infrastructures, this technology produces no greenhouse gas emissions and requires no fuel, making it a promising green energy solution (Prabowoputra et al., 2020; Prasetyo et al., 2022; Lutfi et al., 2023; Rasgianti et al., 2024a).

OTEC operates on the principle of ocean thermal energy conversion, in which heat from surface seawater is used to vaporize a low-pressure working fluid. The resulting vapor drives a turbine to generate electricity (Rajagopalan and Nihous, 2013; Adiputra et al., 2023). After passing through the turbine, the working fluid is condensed back into a liquid using cold seawater from the ocean depths (Nihous, 2007). This closed-loop system comprises several main components, including turbines, heat exchangers (evaporators and condensers), working fluid, and seawater pipes (Avery and Wu, 1994; Adie et al., 2023a).

Numerous studies have been conducted to optimize the OTEC system, especially on its main components. In the development of the turbine system, Alawadhi et al. (2020) used response surface methodology and Computational Fluid Dynamics (CFD) analysis with ANSYS CFX to optimize a radial turbine in an ORC cycle, successfully reducing enthalpy loss and improving turbine power and efficiency. Wu et al. (2019) applied a three-stage optimization process using MATLAB to increase power output by optimizing the volume fraction, turbine wheel diameter ratio, and relative flow angle. Previously, Uehara et al. (1989) used Powell's method and the Hooke–Jeeves pattern search to optimize the mass flow rate and rotational speed of the turbine.

Considerable progress has also been made in the development of heat exchanger systems. Yasunaga et al. (2017) proposed an optimization method based on the ratio of maximum power to pressure drop and Reynolds number. In follow-up research, Yasunaga et al. (2018) refined this approach by balancing heat transfer performance with pressure loss to maximize net power. Additionally, Fontaine et al. (2019) compared the performance of different types of heat exchangers using Carnot and Rankine cycles, revealing that the results are highly dependent on seawater temperature. Fontaine (2022) further optimized the design of plate-type heat exchangers considering the chevron angle and enlargement factor to maximize power per unit area.

The selection of an appropriate working agent is a critical factor in the design of OTEC systems. Ganic and Wu (1980) compared various fluids, such as ammonia, propane, and freon-114, concluding that ammonia offers the best efficiency despite its toxicity. Anderson (2009) reviewed alternatives such as R-134a, R-152a, and hydrocarbons, noting that these fluids strike a balance between thermal efficiency, safety, and cost. Further studies by Yoon et al. (2014) and Yang and Yeh (2014) showed that R717 offers high thermal efficiency, although it poses a toxicity risk, while R744 is considered more environmentally friendly. Finally, Mansour et al. (2020) (Mansour et al., 2020) recommended R134a as the most suitable working fluid due to its cost efficiency and compatibility.

Numerous studies have also been conducted on submarine pipelines or cold water pipe (CWP) systems due to their considerable impact on the OTEC system (Habib et al., 2023; Naufal et al., 2023). For example, a study by Adiputra and Utsunomiya (2022) focuses on pipe stability through FEM analysis. Research by Firmansyah et al. (2024) calculates seawater temperature distribution at various depths and evaluates several pipe materials. Additionally, a study by Rasgianti et al. (2024b) optimized the geometry of ring stiffeners in CWPs.

However, the need for pipes in the OTEC system extends beyond the CWP. Owing to the multiple fluid transfer functions involved, OTEC systems require various types of pipes, each with diverse geometries and materials. While studies

have been conducted on key components (such as the turbine, heat exchanger, working fluid, and CWP), research on supporting structures, specifically the overall piping system requirements, remains limited. Therefore, this study aims to analyze the impact of highly variable geometries on pipe strength in OTEC systems and develop a simple formula for estimating pipe strength. The results of this study are expected to aid in the design and selection of suitable pipes, thereby enhancing the efficiency, safety, and reliability of OTEC systems.

2 Research milestones

The study of piping systems in OTEC has made considerable progress, especially in the development of formulas for calculating pipe moments. Early research on pipe bending moments started with a simple formula by Brazier (1927) based on elastic deformation. The proposed formula, which calculates the pipe reaction moment (RM), incorporates the modulus of elasticity (E), pipe radius (r), and wall thickness (t), as shown in Equation (1). This approach was later developed by Chwalla (1933), who considered infinite deformation of the cross-section, resulting in the formula represented in Equation (2).

$$M = 0.33\pi Ert^2 \quad (1)$$

$$M = 0.378\pi Ert^2 \quad (2)$$

Later studies (Lundquist, 1933) described pure bending tests on duralumin cylinders with circular cross-sections, using rigid bulkheads under bending and compression. These tests led to the derivation of Equation (3), where ν is the Poisson's ratio.

$$M = \frac{2\sqrt{2}}{9} \frac{E\pi r t^2}{\sqrt{1-\nu^2}} \quad (3)$$

The study by Suer et al. (1958) used a semi-empirical approach, combining theoretical analysis with experimental data, to develop a design procedure for predicting the critical bending stress in thin cylinders with circular cross-sections. This approach led to the derivation of Equation (4), which uses Equation (5) for the critical buckling stress, as proposed by Lo et al. (1951).

$$M = \sigma_{cr} \frac{I}{r} \quad (4)$$

$$\sigma_{cr} = C_b E \left(\frac{t}{r} \right) \quad (5)$$

Timoshenko and Gere (2009) later described the pipe moment as the moment generated by the load applied to the pipe, which can lead to flexure and potential structural failure. They proposed an advanced formula, shown in Equation (6).

$$M = 0.786 \, 5 \pi E r t^2 \quad (6)$$

The study by Stephens et al. (1975) presents the buckling moment formula, which builds upon Brazier's theory (Brazier, 1927), as shown in Equation (7).

$$M = \frac{2(2)^{1/2}}{9} \frac{E \pi r t^2}{(1 - \nu^2)^{1/2}} \quad (7)$$

Another study by Chen and Kempner (1976) addressed buckling under compression and bending loads, presenting a formula for the bending moment as shown in Equation (8). In this equation, R is the radius of curvature, P is the applied end thrust, X is the axial coordinate, φ is the specified quantity, and S is the circumferential coordinate.

$$M = \left[\frac{\left(\frac{1}{R} - P \right)}{X_1 \varphi_2 + X_2 \varphi_1} \right]; \min 0 \leq S \leq \frac{\pi}{2} \quad (8)$$

Later, Fabian (1977) presented Equation (9), where S is the half cross-section, $\bar{N}$ is the membrane stresses, Z is the axial location of the material, and ϵ is the axial strain.

$$M = 2 \int_{S_1}^{S_2} \{ \bar{N} (Z - Z_e) \} ds; \bar{N} = \frac{Eh}{1 - \nu^2} \{ \epsilon + \nu \epsilon_s \}; \epsilon = \frac{Z}{\left(\frac{l}{2\pi} \right)} \quad (9)$$

Toward the end of the 20th century, Mork et al. (1997) developed a highly comprehensive formula for the bending moment of pipes, considering elastic deformation. Equation (10), which incorporates material yield strength (σ_y) and pipe diameter (D), is particularly relevant for internal pressure stability analysis.

$$M = \left(1.05 - 0.001 \, 5 \frac{D}{t} \right) \sigma_y D^2 t \quad (10)$$

In the 21st century, a study by Karamanos (2002) developed the formula of Brazier (1927) to calculate the maximum bending moment in pipes by incorporating the effect of the Poisson's ratio, as shown in Equation (11).

$$M = 0.987 \frac{E r t^2}{\sqrt{1 - \nu^2}} \quad (11)$$

A decade later, a study by Yudo and Yoshikawa (2012) proposed a formula developed from the formula proposed by Brazier (1927), considering variables such as length-to-diameter (L/D) ratios ranging from 5 to 20 and diameter-to-thickness (D/t) ratios ranging from 50 to 200. Their study showed that the critical bending moment, based on linear calculations, is expressed by Equation (12).

$$M = 0.666 \pi E r t^2 \quad (12)$$

Later, Yudo and Yoshikawa (2015) provided a formula for the maximum bending moment of long pipes, developed from previous studies, considering oval deformation. The proposed formula is shown in Equation (13).

$$M = 0.314 \pi E r t^2 \quad (13)$$

In the same year, Polenta et al. (2015) developed a formula to calculate the critical moment of a pipe, focusing on the critical stress of the material and the modulus of elasticity. This formula is shown in Equation (14), where p represents the stress due to pressure.

$$M = \left(1.68 D^2 \frac{\sigma_{cr}}{2} + 0.203 D^3 p; \sigma_{cr} = \frac{Et}{r \sqrt{3(1 - \nu^2)}} \right) = \frac{1.68}{\sqrt{3(1 - \nu^2)}} E D t^2 + 0.203 D^3 p \quad (14)$$

The latest study, proposed by Struct X (2024), presented a formula for pipe-bending stress, as shown in Equation (15), where D_i is the inner diameter and D_o is the outer diameter.

$$\sigma = \frac{32 M}{\pi D_o^3 \left[1 - \left(\frac{D_i}{D_o} \right)^4 \right]} \quad (15)$$

From this formula, the pipe bending moment formula is derived, as shown in Equation (16).

$$M = \frac{\sigma \pi D_o^3 \left[1 - \left(\frac{D_i}{D_o} \right)^4 \right]}{32} \quad (16)$$

Thus far, studies on the overall piping system in OTEC have addressed various aspects, including materials, dimensions, and thermal properties. However, previous research has generally been limited to formulas applicable under specific conditions, making them less capable of accommodating highly complex geometric and material variations. Aiming to address this gap, a study was conducted

to develop a predictive formula for pipe moments, incorporating key factors such as pipe length (L), geometric ratios, such as L/D and length-to-thickness (L/t), as well as material properties, as the main variables in the calculation.

3 Methodology

Figure 1 illustrates the flowchart of the study methodology, providing a visual overview of the sequence of procedures, from the initial stage of validating procedure settings to the final stage of developing the flexural capacity estimation formula.

The study methodology began with a benchmarking effort against previous studies to validate the accuracy of the test procedures. Simulation-based numerical testing was conducted using ABAQUS software (Dassault Systèmes Simulia, 2011). During the benchmarking stage, adjustments were made to parameter settings, modules, and result outputs, drawing from previous reference studies. Validation was considered successful when the error was less than 5%.

The case configuration stage involved identifying the parameters that substantially affect the test output (moment), specifically geometric parameters (length, diameter, and thickness) and material properties (yield strength). The FEM module was adjusted based on these parameter varia-

tions, and mesh convergence was performed before testing, resulting in the FEM test data.

The regression analysis stage began with the normalization of the FEM data, followed by the application of a non-linear regression approach to derive the proposed formula. Formula validation was conducted using two methods: comparison with new test data and comparison with similar formulas from other studies. Ten validation tests labeled A, B, C, and so on were conducted with several parameter variations. The FEM results, the proposed formula, and formulas from previous studies were compared. The proposed formula was considered accurate if the FEM test error was less than 10% and its results were closer to the FEM data than those from existing formulas.

3.1 Bending theory

In elastic pipe bending analysis, the curvature or degree of bending experienced by the pipe can be determined using the curvature parameter (λ). The formula for calculating curvature is shown in Equation (17).

$$\lambda = \frac{Rt}{r^2 \sqrt{1 - \mu^2}} \quad (17)$$

where λ is the pipe curvature value, R is the applied exter-

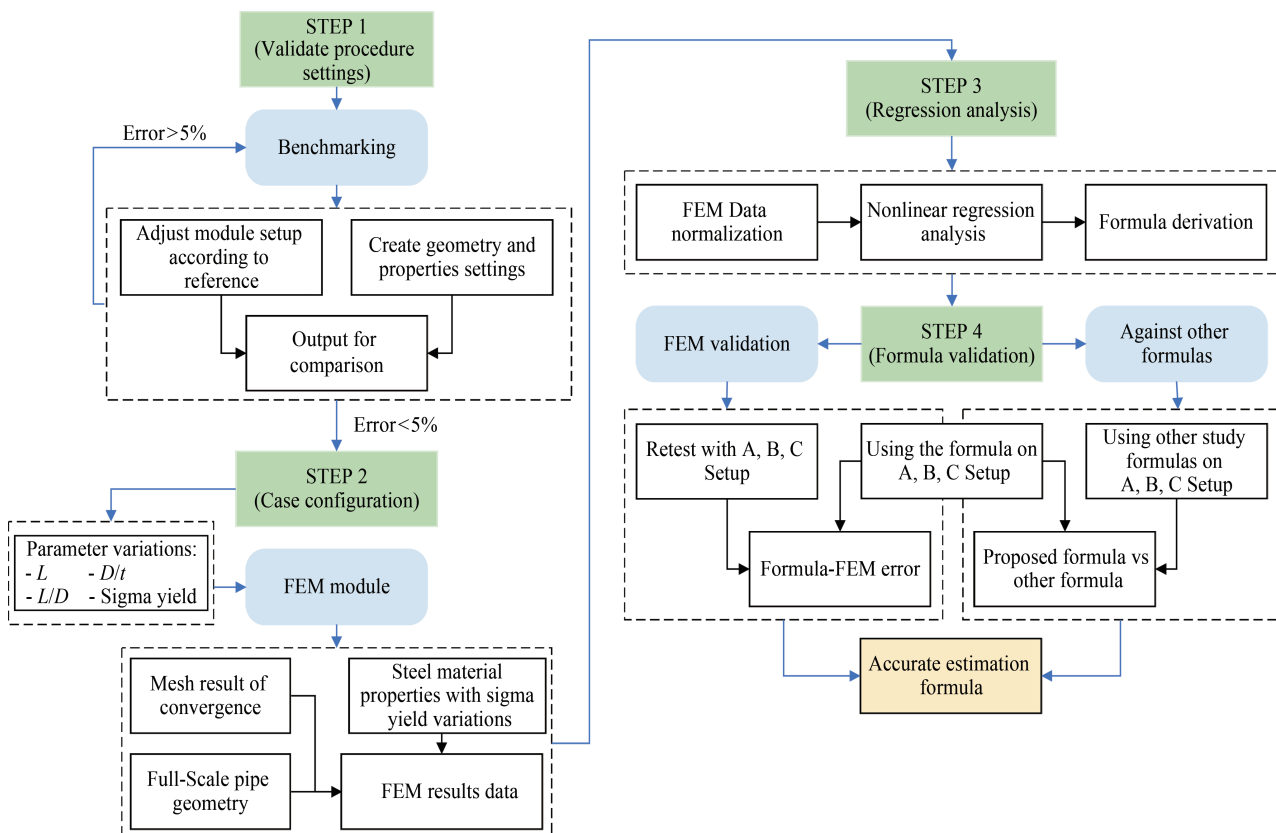


Figure 1 Methodology flowchart of the study

nal radius of curvature, t is the pipe wall thickness, r is the pipe radius, and μ is the Poisson's ratio of the material. This equation helps estimate the deformation of the pipe geometry when subjected to bending, considering the elastic properties and geometry of the material (Elchalakani et al., 2002).

Additionally, the maximum curvature limit, beyond which the pipe deforms further, can be calculated using the bending curvature equation, as shown in Equation (18).

$$K_{BR} = 0.471 \frac{t}{r^2 \sqrt{1 - \mu^2}} \quad (18)$$

where K_{BR} represents the maximum curvature. This equation is crucial for determining the extent to which the pipe can be bent without experiencing shape instability due to excessive ovalization (Karamanos, 2002).

In addition, under elastic–plastic conditions, the total moment considered for cross-sectional analysis can be expressed as Equation (19).

$$M_{tot} = 2KEI_e + 2EKY_e S_p \quad (19)$$

where K is a geometric constant, I_e is the elastic moment of inertia, Y_e is the elastic–plastic distance from the neutral axis, and S_p is the plastic modulus of the cross-section. The values of I_e and S_p can be determined using integrals such as Equations (20) and (21), respectively.

$$I_e = \int_0^{Y_e} Y^2 B(Y) dY \quad (20)$$

$$S_p = \int_{Y_e}^R YB(Y) dY \quad (21)$$

where $B(Y)$ is the stress distribution function at position Y in the cross-section of the structure, with integral limits from 0 to Y_e for I_e and from Y_e to R for S_p . This equation enables a comprehensive analysis of the elastic and plastic contributions in pipe bending under high bending loads, which is essential for understanding the elastic–plastic limits of materials and the stability of structures during loading (Al-Qureshi, 1999).

The bending equations presented are derived based on certain assumptions, including cylinder geometry, material properties, and bending load conditions. These assumptions limit the applicability of the formulas in scenarios involving combined loads or anisotropic materials.

3.2 Regression concept

Regression is a statistical technique used to model the relationship between one or more independent (predictor)

variables and a dependent (response) variable (Montgomery et al., 2021). The main objective of regression is to identify the patterns of relationships between these variables, enabling predictions or inferences from the data (Fumo and Rafe Biswas, 2015). In regression analysis, the dependent variable is often influenced by several independent variables (González-Rogado et al., 2014). Several types of regression are commonly used in analysis, such as linear regression, polynomial regression, and logarithmic regression (Gupta et al., 2017). Each type has specific advantages and applications, depending on data characteristics and the nature of the relationship between the variables being studied (Zhang and Goh, 2013).

Linear regression is the simplest form of regression, where the relationship between the dependent and independent variables is assumed to be linear (Myers et al., 2012). Linear regression models typically result in a straight-line equation, as shown in Equation (22).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \epsilon \quad (22)$$

where y is the dependent variable, x is the independent variable, β is the coefficient to be studied, and ϵ is the error.

In logarithmic regression, the relationship between the dependent and independent variables is not linear but can be described using a logarithmic transformation (Dambolena et al., 2009). Logarithmic regression is often used when data shows an exponential pattern of change or spans a substantially large range. Equations (23) and (24) show the logarithmic regression model.

$$y = \beta_0 + \beta_1 \log(x) + \epsilon \quad (23)$$

Or

$$\log(y) = \beta_0 + \beta_1 x + \epsilon \quad (24)$$

where $\log(x)$ denotes the logarithmic transformation of the independent variable or the logarithm of the dependent variable, if required. In pipe bending moment analysis, logarithmic regression is used to model the nonlinear relationship between the bending moment and variables such as length, diameter, thickness, and yield stress of the pipe material. This approach is particularly useful when the data exhibits a nonlinear growth pattern or when certain variables have remarkably different scales.

The choice of regression type depends on the characteristics of the data and the purpose of the analysis. For pipe bending moments, logarithmic regression was chosen because it more accurately describes the complex relationship between the material and geometric parameters of the pipe, which may not follow a linear pattern. Parameters such as pipe thickness, length, and diameter often indirectly influence the

bending moment, and logarithmic transformation helps clarify this relationship by reducing data skewness and variability.

The main advantage of logarithmic regression lies in its capability to effectively handle nonlinear relationships through transformation. This characteristic enables simpler analysis and better model interpretation, especially when dealing with data that has substantial variations. Zeng and Tang (2011) applied a corrected logarithmic regression model to address the potential bias that may arise when converting predictions back to the original scale of the logarithmic transformation. Their formula successfully reduced negative bias in the prediction results.

However, logarithmic regression has certain limitations. This type of regression requires all input values to be positive, and its performance may decline if the underlying relationship is not truly exponential. Additionally, logarithmic regression can be sensitive to extreme values, which may distort the regression curve.

3.3 Benchmark particulars

A study by Adie et al. (2023b) was chosen as a benchmark in this study due to its comprehensiveness for modeling and numerically testing pipe structures subjected to bending loads, particularly for CWP applications in OTEC technology.

Adie et al. (2023b) replicated the study by Yadav and Gerasimidis (2019) using ABAQUS software. They modeled a cantilever pipe where one end is fixed, and the other end is subjected to bending loads, resembling the operational conditions of a CWP in an OTEC system with a free end. At the fixed side of the pipe, all degrees of freedom are set to zero ($U1 = U2 = U3 = UR1 = UR2 = UR3 = 0$), while at the free end, a moment load is applied through rotational displacement (θ).

In a mesh convergence study, Adie et al. (2023b) conducted mesh analysis, starting with a mesh size of 200 mm and refining it to the minimum size that yielded convergent results. The study found that a mesh size of 55 mm resulted in optimal convergence with stable critical moment values. Aiming to describe the plastic deformation behavior, especially in materials with nonlinear elasticity such as FRP, used the Ramberg–Osgood equation, which models the plastic stress–strain relationship in materials.

With simulation settings and constraints adjusted according to the study by Adie et al. (2023b), the benchmarking test results were obtained, as shown in Table 1. The benchmarking study used steel material with properties that were also adjusted with previous studies, specifically a Young's modulus of 210 GPa, yield strength of 455 MPa, density of 7840 kg/m³, and Ramberg–Osgood plastic mode.

The benchmarking results indicate a strong agreement between this study and the results of Adie et al. (2023b) in calculating critical moments. A comparison of the critical

Table 1 Error comparison to the previous study (Adie et al., 2023b)

Imperfection (W_0/t)	Variable			Critical moment comparison		
	D (mm)	t (mm)	L (mm)	Adie et al. (2023)	Present Study	Error
0.10	10000	100	25000	3.84E+12	4.081E+12	5.905%
0.10	3000	30	100000	9.73E+10	9.881E+10	1.529%
0.10	9000	90	100000	2.68E+12	2.684E+12	0.178%
0.05	9000	90	100000	2.643E+12	2.680E+12	1.401%
Error average						2.253%

moment values from both studies revealed an average error of 2.253%. Overall, the benchmarking step shows that the method and model used in this study effectively replicate those of Adie et al. (2023b) with reasonable accuracy, thereby validating the numerical approach and configuration applied in this study.

3.4 Finite element method analysis

3.4.1 Module settings

The boundary conditions (BCs) for the pipe model in Figure 2 were applied at both ends to simulate the support conditions during the bending test. At the lower end, an encastre condition was applied to fix all degrees of freedom (displacement and rotation). Meanwhile, at the upper end of the pipe, the BC allowed rotational freedom only at UR1,

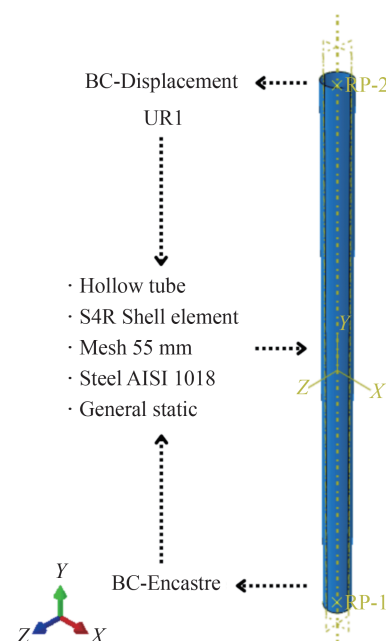


Figure 2 Module settings

facilitating rotation around the X -axis while restricting all other movements. The X , Y , and Z axes correspond to the coordinate orientations, with the applied loading designed to replicate the bending behavior under the specified operating conditions.

The module setting for this simulation uses a general static approach. In this approach, the system solution is determined based on the principle of static equilibrium without considering dynamic effects or large instabilities, as in the Riks method (Felippa and Chung, 1981). The basic static equilibrium formula is shown in Equation (25), where K is the global stiffness matrix, δ is the nodal displacement vector, and F is the external force vector.

$$K \cdot \delta = F \quad (25)$$

The shell element mesh used in this simulation is 55 mm in size, chosen for its capability to sufficiently capture deformation in the pipe during the bending simulation. The S4R shell element was selected due to its high efficiency in modeling thin-walled structures such as pipes, with the mesh containing approximately 40 000 nodes. The use of shell elements, as opposed to solid elements, offers advantages in terms of computational efficiency, making it highly suitable for thin pipe geometries and reducing the overall computational load.

3.4.2 Mesh convergence

Mesh convergence is crucial in finite element simulation analysis because it ensures that the calculation results are independent of the mesh size. The goal of mesh convergence is to achieve accurate results while minimizing computational complexity (Al Kautsar et al., 2024a). Figure 3 shows the mesh convergence analysis, illustrating the relationship between the number of elements and the critical moment. As the number of elements increases, the critical moment sharply decreases until it stabilizes at 42 224 elements (corresponding to a 55 mm mesh). Beyond this point, even though the number of elements continues to increase (i.e., the mesh size becomes smaller), the critical moment remains stable. The 55 mm mesh was selected as the con-

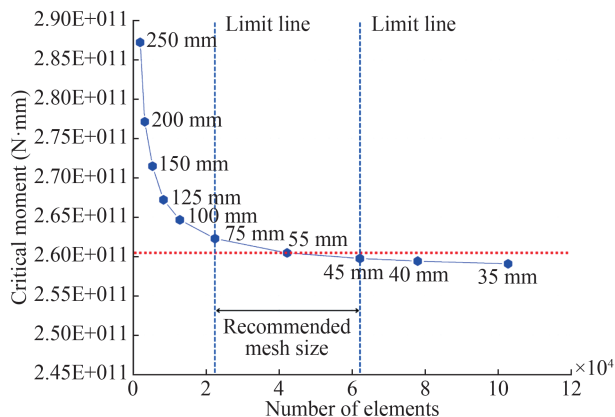


Figure 3 Mesh convergence

vergent mesh because it strikes an optimal balance between result accuracy and computational efficiency.

3.5 Case study configuration

The pipe is assumed to be homogeneous and isotropic, with its material behavior defined by a specified yield stress value. Only bending moment loads are applied, while axial or internal pressure forces are excluded. For simplification, environmental dynamic effects, such as ocean currents or wave-induced loads, are not considered. Geometric imperfections are also assumed to be negligible, consistent with standard assumptions used in controlled simulations of similar FEM studies.

3.5.1 Geometrical model

The selection of the geometrical model in simulations is critical to ensuring the accuracy and relevance of the study results (Al Kautsar et al., 2024b). An appropriate geometric representation ensures that the shape, dimensions, and physical characteristics of the analyzed object closely resemble the actual conditions of the specimen. Geometry directly influences the distribution of forces and pressures, which, in turn, affect the mechanical response or physical behavior of the specimen. Errors in geometry modeling can lead to invalid simulation results. The pipe geometry design used in this study is shown in Figure 4, with the corresponding parameter variations detailed in Table 2.

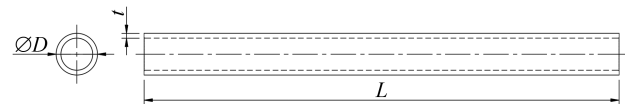


Figure 4 Specimen geometry

Table 2 Geometric variations

L (m)	L/D	D/t
10	20	10
20	100	50
30	200	100
40	300	150
50	400	200

The selected pipe lengths (10–50 m) are consistent with the dimensional scale of chilled water and transfer pipeline systems commonly used in actual OTEC infrastructure, thereby ensuring the practical relevance of the analysis. The L/D ratios used in the simulation, ranging from 20 to 400, were selected to capture the transition in mechanical behavior from rigid, short pipes to flexible, slender pipes, as typically encountered in piping systems subjected to bending loads. Similarly, D/t ratios, ranging from 10 to 200, were chosen to assess structural integrity across a spectrum of conditions, from thick-walled, rigid conditions to thin-walled configurations that are more susceptible to ovalization.

3.5.2 Material properties

This study uses AISI 1080 as the pipe material, with its material properties presented in Table 3. AISI 1080 possesses high mechanical strength, making it suitable for applications requiring materials with substantial load-bearing capacity, such as support structures, floating platforms, or mechanical components operating in marine environments. Owing to its excellent strength and hardness, especially after heat treatment, AISI 1080 is highly suitable for components exposed to dynamic loads, including shafts, pipes, and other structural elements subjected to demanding marine conditions. However, the use of this material in such environments must be accompanied by appropriate coating treatments to mitigate the risk of corrosion. The variation in material properties used in this study is shown in Table 4.

Table 3 AISI 1018 material properties (Kyriakides et al., 2008)

Young's Modulus	Ultimate Strength	Density	Poisson's Ratio
210 GPa	455 MPa	7.840 kg/m ³	0.3

Table 4 Material properties variation

Yield strength (MPa)			
355	315	285	235

4 Variation effects

4.1 Length variation effects

For the length variation analysis, a geometry with an L/D ratio of 20, a D/t ratio of 10, and a yield stress of 315 MPa was selected to represent the comparative pipe lengths. The yield stress value of 315 MPa represents the typical strength range of structural steel pipes. Pipe length notably influences structural stiffness and stress distribution under bending loads. Pipe length is directly proportional to structural flexibility. In longer pipes, the greater distance between support points and the load application point generates a larger bending moment for each unit of applied force, resulting in increased bending effects.

Figure 5 shows the bending moment–curvature graph for various pipe lengths. The 10 m pipe shows a relatively low bending moment compared to longer pipes, indicating that shorter pipes are stiffer and reach their saturation point more quickly. By contrast, the 50 m pipe exhibits a substantially higher bending moment, indicating that it can endure greater bending loads before reaching its maximum curvature. The graph also shows that longer pipes require greater curvature for the bending moment to stabilize, reflecting their increased flexibility.

Figure 6 shows the deformation contours for pipes with different lengths. The 10 m pipe displays a relatively low-

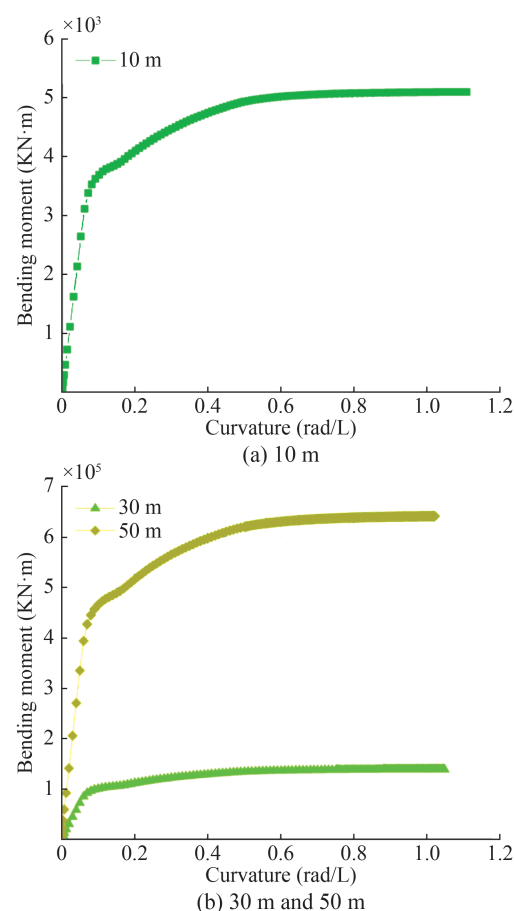


Figure 5 Bending moment–curvature graph of length variation

stress distribution and minimal deformation, indicating that shorter pipes experience limited deformation under load. By contrast, longer pipes exhibit higher stress levels and more pronounced deformation. The stress distribution in these longer pipes is more widespread, with greater intensity, resulting in increased flexibility and a greater tendency to bend under the same applied load.

The results of length (L) variation were validated against the previous study by (Chen et al., 2022), which discussed the effect of pipe diameter variation on bending moment capacity. Although the study focused on diameter, the change in diameter can be associated with variations in element length or slenderness ratio, as smaller diameters are often associated with the use of longer element lengths in practical design applications.

The study shows that a smaller diameter (or element length) results in a lower maximum bending moment value, as shown in Figure 7. However, this trend differs from the results of the current study, which indicate that the bending moment increases as the pipe length increases. This difference can be attributed to the geometry approach used in this study, where the parameters L , L/D , and D/t were varied simultaneously. By maintaining constant L/D and D/t values, any increase in length L is accompanied by proportional

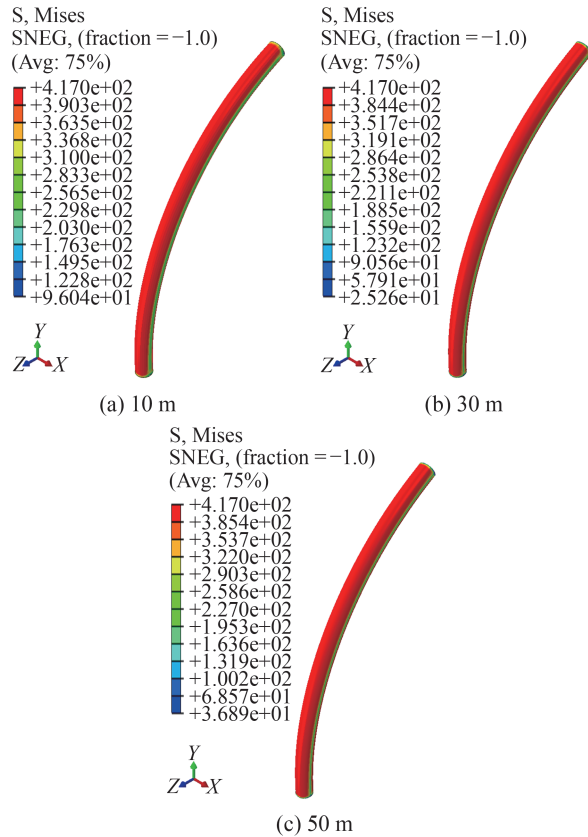


Figure 6 Pipe deformation contour of length variation

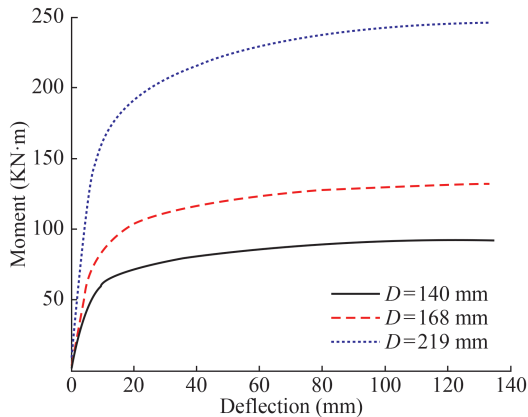


Figure 7 Effect of external diameter of steel tube on the bending moment (Chen et al., 2022)

increases in pipe diameter (D) and thickness (t) values. Consequently, this phenomenon raises the cross-sectional moment of inertia (increased sectional stiffness), allowing the pipe to withstand greater bending loads and resulting in a higher bending moment.

These findings have practical implications for the design of marine piping systems, particularly in OTEC applications, which often require long pipelines. The increased flexibility and deformation observed in longer pipes indicate a higher risk of structural instability and excessive bending under operational loads. This finding highlights the need to treat pipe

length as a critical design parameter. For example, in deep-sea applications, pipes that exceed certain lengths may require additional reinforcement, support structures, or stiffness optimization to ensure mechanical integrity.

4.2 Length-to-diameter (L/D) ratio effects

Figure 8 displays the relationship between bending moment and curvature for various L/D ratios with 20, specifically 100, 200, 300, and 400 values. This graph shows

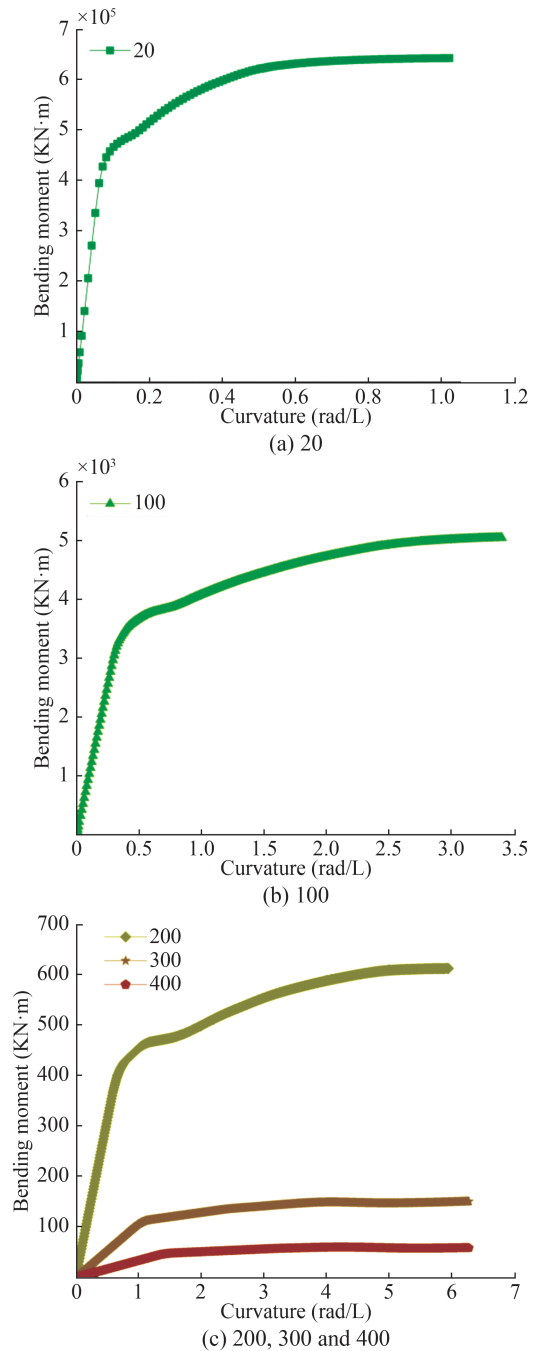


Figure 8 Bending moment-curvature graph of length-to-diameter variation

that differences in the L/D ratio notably affect the strength and flexibility of the pipe. For smaller L/D ratios, such as 20, the pipe is stiffer, requiring a higher bending moment to produce curvature. Conversely, for larger L/D ratios, such as 400, the pipe becomes more flexible, and curvature changes occur with relatively smaller bending moments. This finding indicates that as the L/D ratio increases, the pipe becomes more susceptible to bending deformation.

Figure 9 shows the deformation contours for various L/D ratios. The deformation is minimal for pipes with a small L/D ratio, indicating higher stiffness. The deformation then becomes more prominent for pipes with larger L/D ratios, revealing that the pipe becomes more flexible and prone to shape changes when subjected to load. These deformation contours emphasize that as the L/D ratio increases, the pipe experiences considerable deformation, highlighting increased flexibility and decreased stiffness.

The effect of L/D variation in this study was then validated by a previous study by Visuvasam and Chandrasekaran (2022), which examined the impact of the slenderness ratio of foundation piles on the seismic response of buildings using shake table tests on building models supported by groups of piles. In their study, Visuvasam and Chandrasekaran (2022) demonstrated that the variation in the L/D ratio affects the maximum bending moment along the pile element, with the highest maximum moment value occurring at the smallest L/D , as shown in Figure 10. Although the parameters in the study of Visuvasam were plotted against normalized depth (bending moment vs. normalized depth), the observed trend remains consistent: the smaller the L/D ratio, the greater the bending moment.

4.3 Diameter-to-thickness (D/t) ratio effects

Figure 11 shows the graph of the relationship between bending moment and curvature for variations in the D/t ratio. At a D/t ratio of 10, the pipe experiences minimal deformation because the relatively large wall thickness compared to the diameter provides higher stiffness, enabling the pipe to resist bending forces effectively without substantial shape changes. As the D/t ratio increases to 50 deformations slightly increases due to the still relatively large wall thickness. At a D/t ratio of 100, the pipe begins to show more extensive deformation as the wall thickness becomes smaller, reducing stiffness and increasing the pipe's response to bending forces. At a D/t ratio of 150, the deformation becomes even more pronounced, reflecting further reductions in stiffness. Finally, at a D/t ratio of 200, the pipe exhibits the largest deformation because the notably thin wall thickness drastically reduces stiffness, increasing the vulnerability of the pipe to deformation.

Figure 12 shows that at smaller D/t values, the deformation is more evenly distributed along the pipe, indicating superior structural integrity. However, as the D/t ratio increases, the structure becomes more flexible, leading to

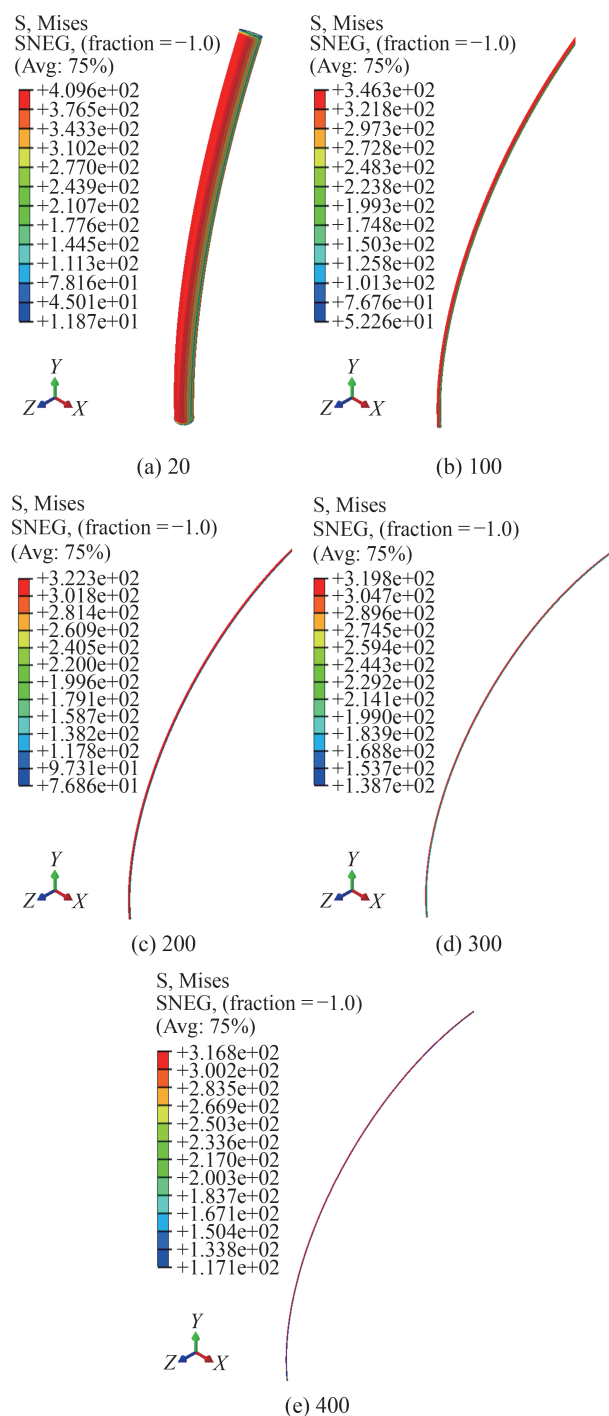


Figure 9 Pipe deformation contour of L/D variation

higher deformation and stress concentration, which can lead to structural failure at critical points under excessive load.

The results of the D/t variation were validated against a previous study by Alzabeebee et al. (2019), which discussed the economic design of buried concrete pipes subjected to standard traffic loads. The study performed a numerical analysis to assess the effect of pipe wall thickness on the distribution of the bending moment due to surface

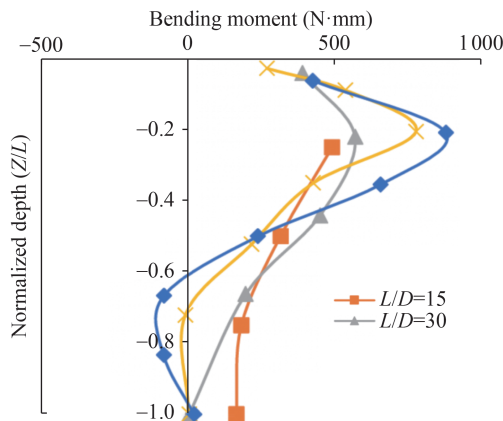


Figure 10 Influence of pile slenderness on bending moment (Visuvasam & Chandrasekaran, 2022)

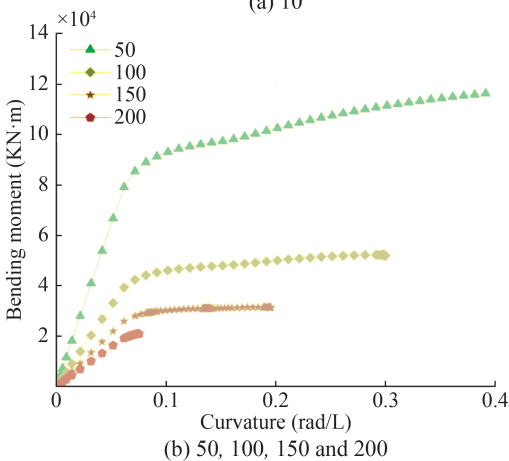
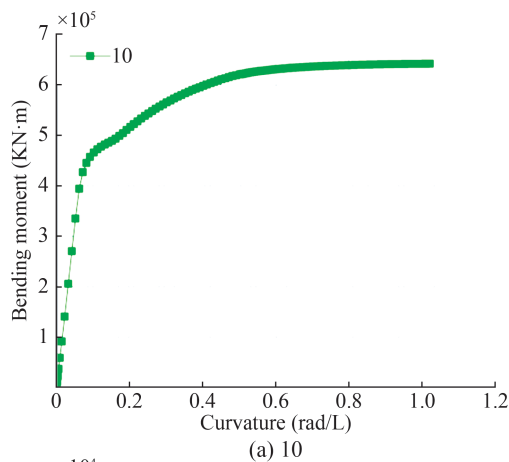
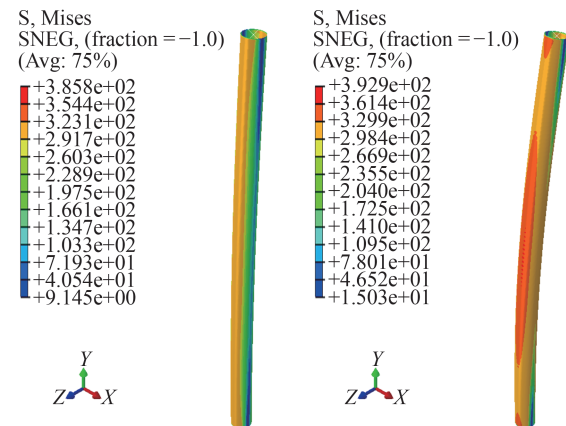


Figure 11 Bending moment–curvature graph of D/t variation

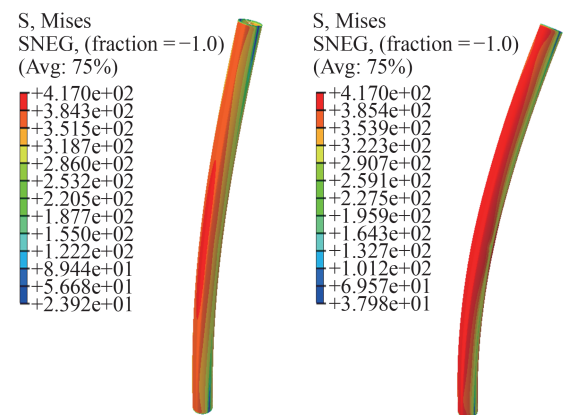
loads. They varied the pipe thickness and evaluated the bending moment along the pipe circumference at different angles.

The study showed that varying the wall thickness (t) had a considerable effect on the maximum bending moment value, as shown in Figure 13. Pipes with greater thickness generate higher bending moments because their increased stiffness causes the distribution of additional soil load to



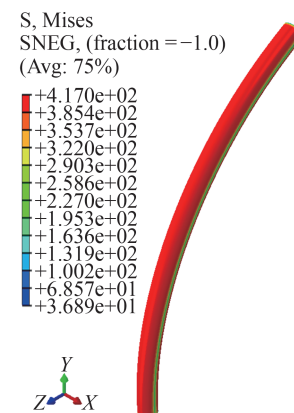
(a) 10

(b) 50



(c) 100

(d) 150



(e) 200

Figure 12 Pipe deformation contour of D/t variation

the pipe. Although Alzabeebee et al. (2019) presented a relationship between the bending moment and the crown angle, the trend observed remains relevant: the greater the pipe thickness, the higher the bending moment.

4.4 Yield stress variation effects

Figure 14 shows the graph of bending moment versus

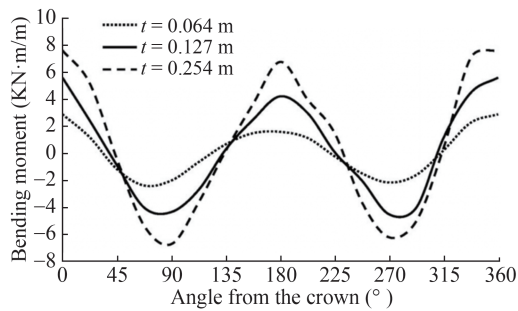


Figure 13 Effect of thickness on the bending moment (Alzabeebee et al., 2019)

curvature for pipes made from materials with different yield stresses. The graph shows that materials with lower yield stress are more prone to deformation under relatively small bending moments. Additionally, the graph for these materials shows that plastic deformation begins earlier, and they are unable to withstand substantial load before reaching the failure point. For materials with higher yield stress, the graph shows that these materials are more resistant to deformation and require a greater bending moment to induce bending.

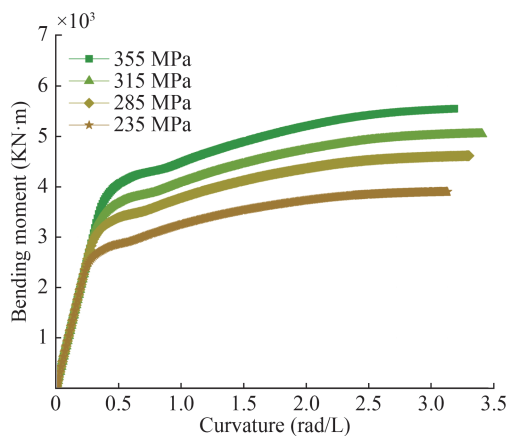


Figure 14 Bending moment–curvature graph of material yield stress variation

Figure 15 compares the deformation contours of the pipes based on variations in the material's yield stress. At a yield stress variation of 355 MPa, the pipe shows minimal deformation, indicating that the pipe can withstand the load without considerable deformation. As the yield stress value decreases, the deformation contours show progressively greater deformations. That is, materials with lower yield stress are more easily deformed under the same bending load, indicating a reduction in material strength as the yield stress decreases.

This observation is validated by Chen et al. (2022), who discussed the flexural capacity of concrete-filled microscale steel tube piles through a numerical approach. The study modeled the relationship between bending moment and

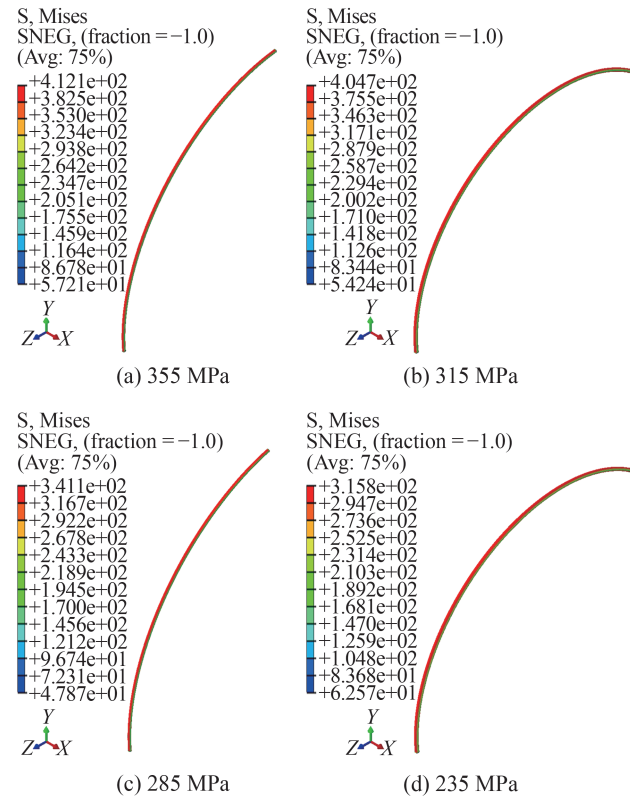


Figure 15 Pipe deformation contour of material yield stress variation

deflection at midspan by varying the yield strength of the steel material (Q235, Q345 and Q390). The study showed that an increase in the yield strength of the steel leads to a higher maximum bending capacity that the structural element can withstand. The highest bending moment values were obtained with the material having the largest yield strength (Q390), indicating that the yield strength of the material plays a crucial role in determining the structural capacity, as shown in Figure 16.

In the current study, variations were made to the material's yield stress value, which is mechanically equivalent to the yield strength for structural steel that does not exhibit a

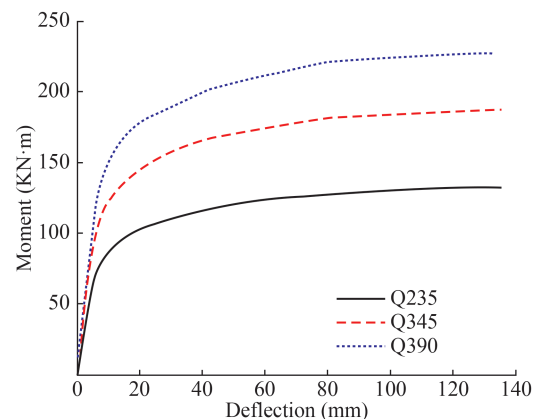


Figure 16 Effect of yield strength of steel on the bending moment (Chen et al., 2022)

long yield plateau. Both terms refer to the yield strength parameter of the material, which functionally affects the flexural capacity. Therefore, the trend of increasing bending moment as the yield stress increases can be validated.

5 Data-driven relationship modeling

The study focuses on developing a data-driven predictive model based on simulation results to estimate the bending capacity of pipes used in OTEC applications. Through regression analysis of varying simulation data, the model determines the mathematical relationship between key variables, such as geometric parameters, material properties, and the structural response of pipes under bending loads. This model can be used to design pipes and make highly accurate predictions tailored to the specific needs of OTEC systems.

5.1 Governing equation

The development of the predictive model begins with the collection and analysis of simulation data from 300 samples. Each simulation yields different bending capacity values depending on the variations of input parameters, such as diameter, thickness, pipe length, and material properties, as shown in Equation (26).

$$L, D, t, \sigma \rightarrow M \quad (26)$$

These values are then made nondimensional to simplify the analysis and factorization and serve as a prediction function, resulting in the form shown in Equation (27).

$$f\left(\frac{L}{D}, \frac{L}{t}\right) = \frac{M}{\sigma L^5/t^2} \quad (27)$$

Therefore, a basic conjecture equation can be formed using these variables as in Equation (28).

$$M = 10^a \left(\frac{L}{D}\right)^b \left(\frac{L}{t}\right)^c \left(\frac{\sigma_y \cdot L^5}{t^2/0.6785}\right) \quad (28)$$

The regression process was used to determine the coefficients in the equation that describe the relationship between the parameters and flexural capacity while considering the statistical significance of each variable. A polynomial equation was chosen for the regression model due to its capability to effectively capture the nonlinear relationship between the independent variables and flexural capacity. The coefficients for each variable were calculated, and the results are presented in Table 5.

The results of the regression enable the identification of the variables that substantially impact flexural capacity and assess the contribution of each variable to the overall model.

Table 5 Regression analysis results

Coefficients			Regression statistics	
Intercept	L/D	L/t	R^2	$Adj. R^2$
2.8299057	-1.835227	-3.11641	0.9712557	0.9676951

With regression statics of 0.971 R^2 and 0.968 *Adjusted* R^2 , respectively, the analysis demonstrates a high level of accuracy in estimating the model. The final equation, obtained after the regression analysis and normalization process, is presented in Equation (29). This equation includes the effects of the key independent variables, providing a reliable basis for accurately estimating flexural capacity.

$$M = \left(10^{2.8299} \left(\frac{L}{D} \right)^{-1.835} \left(\frac{L}{t} \right)^{-3.116} \left(\frac{\sigma_y \cdot L^5}{t^2/0.6785} \right) \right) / 0.6785 \quad (29)$$

5.2 Equation validation

Once the predictive equations are successfully developed, the next step is to validate the model using simulation data as a reference. This validation ensures that the developed predictive equations can consistently replicate the simulation results with high accuracy. Aiming to eliminate any bias in the model, residual analysis is performed. The residual value, which represents the difference between the predicted results and the simulated data, is analyzed to detect any bias patterns that could affect the prediction accuracy. The comparison of the residual values of the result data is presented graphically, as shown in Figure 17.

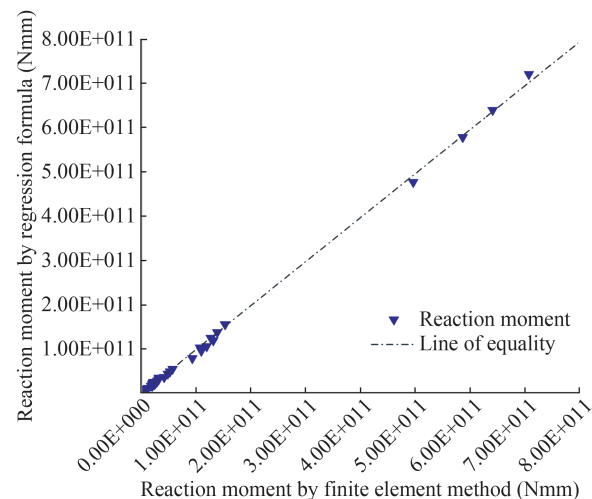


Figure 17 Comparison of FEM and formula data

The closeness of most points to the equality line indicates that the regression formula provides a high level of accuracy in estimating the reaction moment based on the FEM simulation results. The validity of the formula was further confirmed by conducting additional tests with geometries that

varied beyond the tested values. The comparison between the validation test results and the data predicted by the formula is presented in Table 6.

Table 6 Comparison with other variable tests

No	Variable				Moment		Error
	L (m)	D (m)	t (m)	σ_y (MPa)	FEM	Formula	
1	15	0.75	0.075	235	1.336E+10	1.291E+10	3.51%
2	15	0.75	0.100	315	2.31E+10	2.385E+10	3.16%
3	20	1	0.100	355	4.519E+10	4.621E+10	2.22%
4	20	0.5	0.050	355	5.617E+09	5.976E+09	6.02%
5	40	2	0.200	355	3.99E+11	3.697E+11	7.91%
6	40	1	0.100	315	4.092E+10	4.242E+10	3.55%
7	40	2	0.400	315	7.266E+11	7.111E+11	2.18%
8	60	3	0.300	355	1.22E+12	1.248E+12	2.32%
9	60	3	0.500	285	1.69E+12	1.772E+12	4.61%
10	70	3.5	0.500	235	1.938E+12	1.953E+12	0.76%
Average error						3.62%	

The average error between the predicted values and the FEM results was recorded at 3.62%, demonstrating that the predicted formula has good accuracy in estimating the reaction moment for a wide range of pipe geometries. The largest error was 7.91%, while the smallest was 0.76%, both of which fall within a reasonable tolerance range. Thus, this

predictive model serves as an efficient and accurate tool for designing pipes in OTEC applications, enabling fast and precise estimation of bending capacity without the need for new simulations for each configuration.

Figure 18 presents a comparison between the FEM results, considered as validation benchmarks, the derived formulas, and the results from previous studies in predicting the pipe reaction moment under flexural loading conditions. The governing equation demonstrates the best performance because most points are closely aligned with the line of equality, indicating high accuracy and a better capability to replicate the FEM simulation data compared to the other methods. The performance comparison of the derived formulas is also shown in Table 7, revealing that the governing equation yields the least percentage error.

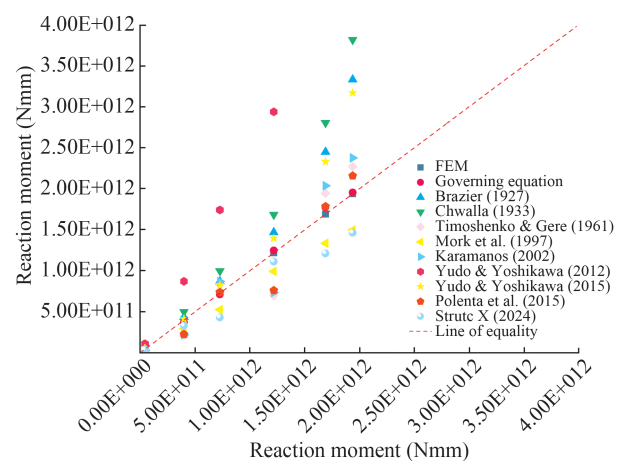


Figure 18 Comparison with other formulas against the equality line

Table 7 Error comparison with other formulas

Formula	Error
Governing Equation	3.62%
Brazier (1927)	24.01%
Chwalla (1933)	33.66%
Timoshenko & Gere (2009)	45.28%
Mork et al. (1997)	27.94%
Karamanos (2002)	41.42%
Yudo & Yoshikawa (2012)	62.01%
Yudo & Yoshikawa (2015)	20.14%
Polenta et al. (2015)	35.59%
Strute X (2024)	24.38%

Aiming to ensure an accurate prediction of the output moment, the constraints must be determined, and recommendations for the application of the derived formula must be provided. The constrained governing equation is obtained as shown in Equation (30).

$$M = \left(10^{2.8299} \left(\frac{L}{D} \right)^{-1.835} \left(\frac{L}{t} \right)^{-3.116} \left(\frac{\sigma_y \cdot L^5}{t^2 / 0.6785} \right) \right) / 0.6785$$

for $20 \leq \frac{L}{D} \leq 400$ and $200 \leq \frac{L}{t} \leq 80\,000$ (30)

6 Conclusions

The study conducted a comprehensive analysis of the effect of variations in pipe geometry and material properties. Various parameters, such as pipe length, diameter, thickness, and material yield stress, were systematically modified to examine their effects on the ultimate bending capacity of the pipe. The results show that each parameter variation notably impacts the flexibility and strength of the pipe in resisting bending moments. Specifically, pipes with larger length ratios tend to be more flexible compared to those with relatively small length ratios. Additionally, smaller L/D and D/t ratios result in stiffer pipes. The analysis also shows that materials with lower yield strength variations are more prone to deformation under bending loads.

The regression analysis in the study successfully developed a predictive formula to estimate the ultimate flexural capacity of the pipe. The formula predicted the flexural capacity with high accuracy, revealing an average error of 3.62% compared to the FEM results. The obtained formula allows for highly efficient decision-making in design without requiring a new simulation method for each configuration and helps optimize the structural performance of OTEC applications.

The proposed regression-based formula was tested against several empirical models from previous studies. As presented in this work, the proposed model can consistently outperform the formulas from previous studies in terms of prediction accuracy. Although formulas from other studies exhibit error margins between 20% to over 60%, the newly developed regulative formula achieves an average error of less than 10%. This performance demonstrates the advantage of the data-driven regression approach in capturing the nonlinear interactions between geometric and material parameters. Thus, such accuracy is particularly crucial in the context of OTEC pipeline design, where structural reliability is highly sensitive to parameter variability.

The limitations of the current study lie in the simplified assumptions made to focus on key structural variables and develop a predictive model with manageable complexity. The material behavior was assumed to be homogeneous

and isotropic, excluding the consideration of composite or layered materials commonly used in marine structures. Environmental dynamic effects, such as wave loads, currents, or thermal gradients, were excluded from the analysis, which concentrated solely on the flexural response of the pipe. Furthermore, only pure bending loads were applied, neglecting the effects of combined stress conditions. Validation was performed through numerical comparison with published FEM results without experimental testing. These limitations may affect the direct applicability of the results to complex, real-world conditions, indicating areas for future studies to address these factors.

Funding Supported by the Ocean Research for Blue Economy research program administered by BRIN's Research Organization for Earth Sciences and Maritime under a project entitled "Utilization of Internal Wave Phenomena for Ocean Thermal Power Plant (OTEC) Optimization: Case Study of Ambon Bay" with contract number B-33360/III. 4/TK. 01.01/12/2024. The authors acknowledge the support.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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